Why has the Arctic warmed?

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Abstract

Arctic temperature has warmed since 1979, with a supposition being that sea ice decline has been the primary cause for overall Arctic tropospheric temperature rise (and 1000-500hPa thickness increase). Using climate simulations we quantify the magnitude of Arctic warming resulting from various factors. Sea ice decline, while having caused much of the near-surface Arctic warming, is shown to have contributed only about 20% to the observed tropospheric warming. The Arctic troposphere has warmed primarily due to remote forcing by natural fluctuations in sea surface temperatures mainly outside the polar cap, explaining about 50% to the observed tropospheric warming. The sea ice contribution to Arctic warming is shown to be less than a warming effect resulting from unforced random atmospheric variability, which may explain up to 25% of the magnitude of observed Arctic tropospheric temperature increase. An implication of these results is that the Arctic troposphere has been mainly responding to rather than forcing mid-latitude weather and climate. The results further suggest that a reduced rate of tropospheric warming or even short-term cooling may occur in the Arctic in the future in response to remote forcing by natural decadal modes of variability.

1. Introduction

During recent decades temperature increases have been larger over the Arctic than over the rest of the globe, especially at the Earth's surface but also in the troposphere (e.g., Lawrence et al. 2008; Graversen et al. 2008; Serreze et al 2009; Bekryaev et al. 2010; Screen and Simmons 2010; Screen et al. 2012). The observed enhanced warming of the Arctic, referred to as Arctic Amplification (AA), has been most pronounced during fall and early winter (Screen et. al 2012; Screen et al. 2013a). The period of AA has generally coincided with accelerated Arctic sea ice loss, especially post-2000 (Stroeve et al. 2007; Comiso et al. 2008; Kumar et al. 2010; Parkinson and Comiso 2013). In September 2012, new record minima for the post-1979 satellite period were reached in both Arctic sea ice extent and ice area, with values descending well below previous records set in 2007 (Parkinson and Comiso, 2013).

The explanation for observed Arctic tropospheric warming is a matter of controversy. It has been conjectured that the magnitude of the Arctic warming throughout the lower-to-middle troposphere, as manifested by widespread increases in the 1000 -500 hPa layer thickness, has been largely driven by Arctic sea ice loss (Francis and Vavrus 2012). However, numerical experiments using climate models forced by observed changes in Arctic sea ice find that the effects of sea ice loss on Arctic temperatures are primarily confined to the lowermost troposphere (e.g., Deser et al. 2010; Kumar et al. 2010; Screen et al. 2012; Screen et al. 2013a). These modeling studies suggest that Arctic amplification of warming throughout the lower-to-middle troposphere is unlikely to be due primarily to sea ice loss. Alternate explanations for the observed warming aloft in the Arctic include increased poleward heat transport related to SST changes that have occurred outside the Arctic (Bitz and Fu 2008; Screen et al. 2012). However, the nature of the SST changes, for instance whether they are linked to natural or anthropogenic variations, has not been determined.

The debate on why the Arctic has warmed is important for interpreting how Arctic changes may be linked to mid-latitude weather variability. The question of how observed sea ice losses have affected the vertical structure of recent Arctic temperature changes is of particular interest, with important implications for determining possible effects of sea ice changes on extreme weather in mid-latitudes. That Arctic sea ice loss may have led to major changes in mid-latitude weather and climate has been conjectured based primarily upon results from several empirical studies (Overland et al. 2010; Francis and Vavrus 2012; Tang et al. 2013). The proposed mechanism that has received most attention to date starts by assuming that Arctic sea ice loss has been a primary driver of Arctic 1000-500mb thickness increases, especially during October to December. A smaller meridional thickness gradient between polar and mid-latitudes implies a weaker upper-level westerly jet, which is proposed to slow the eastward progression and increase the meridional extent of mid-latitude Rossby waves, producing more persistent and extreme weather conditions (Francis and Vavrus 2012). The hypothesis that sea ice loss leads to significant changes in mid-latitude variability therefore rests fundamentally upon the relative importance of sea ice contributions to driving observed Arctic thickness changes. Here, we address the specific question of the strength of this critical first link in the chain proposed to connect sea ice depletion to mid-latitude weather extremes.

2. Reanalysis data sets and model experiments

Observed changes are estimated from four reanalysis data sets: NCEP/NCAR (Kalney et al. 1996), NCEP-DOE (Kanamitsu et al. 2002), ERA-interim (Dee et al. 2011), and JRA25-JCDAS (Onogi et al. 2007). Monthly gridded values for 1000-500 hPa thickness and tropospheric air temperatures are available for each data set from January 1979 through December 2012.

Climate simulations are based on two atmospheric models: CAM4 (Neale et al. 2013) run at 0.94^{o} latitude x 1.25^{o} longitude resolution, and ECHAM5 (Roeckner et al. 2003) run at T156 (~0.75^{o}) resolution. Table 1 gives an overview of all experiments. The fully forced (FF) experiments involve specified observed monthly varying sea surface temperature (SST), sea ice concentration (SIC), and greenhouse gas concentrations from January 1979-December 2012. A parallel set of runs use climatological repeating seasonal cycle of SIC (FixedSIC), while all other forcings evolve as in the FF runs. In this set of runs we also take into account the SST changes due changes in SIC. Specifically, at each grid box, which is partially covered by sea ice, the SST is set to the 1979-1989 climatology (see Screen et al. 2013a for detailed discussion of approach). We estimate the effect of Arctic sea ice change during 2003-2012 alone based on the 2003-2012 decadal mean residuals between the FF and FixedSIC ensembles. This approach allows the most complete interactions among the climate system components independent from sea ice.

Finally, a third set of experiments are subjected to an estimate of the time varying natural component of global SSTs (NatSST) only (described further below), while all radiative forcings and SIC use climatological repeating seasonal cycles. We also utilize a 300-year control experiment in which climatological observed SST, SIC and radiative forcings (RF) for 1981-2010 conditions (CTL) are prescribed.

The principal diagnosis is of changes between the two decadal periods 1979-1988 and 2003-2012 during October to December (OND) when the impact of Arctic sea ice loss on the atmosphere is maximized (e.g. Serezze et al. 2009; Screen et al. 2012; Screen et al. 2013a). Figure 1 (top) shows that SIC reduction between these periods covers most of the Arctic marginal seas with maximum loss between 15°E and 210°E. Outside the Arctic, SSTs are also substantially different between these periods (Fig. 1 middle). In particular, the North Atlantic exhibits widespread warming, whereas the Pacific Ocean is characterized by a horseshoe-like pattern of change having anomalously warm extratropical waters surrounding a colder than normal tropical east Pacific, consistent with the negative phase of the Pacific Decadal Oscillation (PDO). The middle and high latitude oceans of the Northern Hemisphere have experienced strong warming during this recent period (Fig. 1, middle right).

To estimate the contribution of long-term change to the SST differences between the two decades, the linear trend of observed SST from 1880 to 2011 is removed from the monthly varying time series using the Hurrell et al. (2008) data set. Trends are calculated in zonal bands and the zonally-dependent regression coefficients are used to determine the long-term change contribution during the 1979-2012 year period. The 2003-2012 versus 1979-1988 SST differences in this residual data (which are used in the NatSST runs) are only subtly different from the raw data (Fig. 1, bottom) indicating that most of the decadal SST differences for this period were likely due to a natural fluctuation rather than long-term change. The long-term change component consists of weak warming at all latitude bands, being somewhat greater in the tropics and Southern Hemisphere and weak in the middle and high latitudes of the Northern Hemisphere (bottom right), a pattern consistent with coupled model simulations of the ocean response to external radiative forcing change over the last century (Bindorf et al. 2013).

3. Results

Figure 2 compares reanalysis and climate model simulated changes in OND zonal mean temperature between the two decadal periods 2003-2012 and 1979-1988. The average of four reanalysis products (top) reveals strong near-surface warming in the Arctic, with amplified high latitude warming relative to mid-latitudes mainly below 850 hPa. This latitude-height structure is consistent with previous studies focusing on slightly different periods or months (e.g., Kumar et al. 2010; Serreze et al. 2009; Screen et al. 2013a). And whereas different reanalysis products differ in the magnitude of warming (e.g. Bitz and Fu 2008; Grant et al. 2008; Thorne 2008; Screen et al. 2012), the latitude-height structure is very robust to analysis uncertainty (not shown).

This pattern of tropospheric warming is strongly forced, as indicated by the results of the ensemble averaged climate model simulations subjected to the observed changes in global SSTs, sea ice concentration and radiative forcing (Figure 2, second row). The results are furthermore highly reproducible between two different climate models (compare left and right panels). The ensemble responses to prescribed forcing in both models indicate wide-spread warming of the troposphere in middle and high latitudes being strongest near the surface across the Arctic. The model results indicate that much of the vertical structure and the magnitude of Arctic warming has resulted from lower boundary and external radiative forcings, the nature of which is analyzed further below.

Climate simulations that do not account for observed changes in Arctic sea ice concentration (and attending changes in SSTs) fail to produce polar amplification in low tropospheric warming (Fig. 2, third row). These simulations do, however, reproduce virtually all of the middle and upper tropospheric warming occurring in the fully forced experiments. The forced component of deep column warming over the Arctic has thus resulted from mechanisms unrelated to in situ Artic lower boundary changes. To illustrate the nature of the sea ice affect, the residual change between the FF and FixedSIC simulations for the period 2003-2012 is determined, the results of which are presented in the bottom row. Changes in zonal mean temperatures due to sea ice loss alone are confined to the lowermost troposphere, a result robust between the two models and consistent with a series of previous studies on the effect of sea ice loss on the Arctic atmosphere (e.g., Deser et al. 2010; Kumar et al. 2010; Screen et al. 2012; Screen et al. 2013a).

To further assess why the Arctic has warmed, the full statistical distribution of model simulations is diagnosed so as to discriminate between warming contributions by forced signals and those by random atmospheric variations. We diagnose 1000-500 hPa thickness for an area-average over the polar cap (60°N-90°N). An observed thickness increase over this region has been speculated to be mostly due to Arctic sea ice loss with a conjectured chain of causal effects including weakening of the midlatitude westerlies and an alteration in midlatitude weather patterns (Francis and Varvus 2012). The magnitude of deep tropospheric warming occurring over the polar cap resulting from sea ice depletion is the key link upon which the hypothesized midlatitude responses to sea ice loss largely hinges. We determine Probability Distribution Functions (PDFs) of simulated OND thickness change based on a large ensemble approach[1]. The CAM4 and ECHAM5 models yield very similar results (not shown) and thus the models are combined, which allows generating ensembles of the size of 500 to 870 members. The shape of the resulting PDFs are estimated from a non-parametric fit to the multi-model combined large samples.

Figure 3 (top) shows the statistical distribution of 1000-500 hPa thickness change occurring in the fully forced experiments (red curve), together with four reanalysis estimates (dotted red lines). Also shown is a PDF of decadal differences determined from the two 300-year control runs of the atmospheric model in which there are no variations in either ocean boundary or external radiative forcings (black curve). Reanalysis estimates range from thickness increases of 15m - 20m, while the one standard deviation of internal atmospheric decadal variability in 1000-500 hPa thickness is about 4m. The comparison of

[1] The large ensembles are created by differencing each of the 1979-1988 averages from each of the 2003-2012 averages of a particular models' (10 to 20) member ensemble of the forced runs as well as by differencing individual decades of the 300 year control runs. We have verified that there is no statistical correlation between decadal averages, aside from that occurring due to effects of specified forcing.

observations and unforced simulations thus indicates that the observed thickness increase (and the attending 1000-500 hPa column averaged warming over the polar cap of about +1K[2]) is inconsistent with internal atmospheric variability alone. The observed thickness increase over the polar cap is consistent, however, with the statistics of change occurring in the fully forced simulations whose mean value is about 14.1m. The column tropospheric warming that has occurred over the polar cap is thus interpreted to have resulted from strong forcing, with a superposed random component of warming corresponding to about one standard deviation of internal atmospheric decadal variability.

Figure 3 (bottom) shows the statistical distribution of 1000-500 hPa thickness change due to specific ocean boundary forcings which are estimated from parallel suites of model experiments. First, the effect of sea ice loss alone, estimated residually as in Fig. 2, shows a mean thickness increase of 3.5m which corresponds to column warming of about 0.18K (blue curve). This weak signal of sea ice loss for 1000-500 hPa thickness is consistent with the constrained vertical extent of sea ice induced warming which was shown to be mostly confined to the planetary boundary layer (see Fig. 2). The overall weak tropospheric column warming due to decadal sea ice depletion is furthermore less than one standard deviation of internal decadal atmospheric variability, and thus has low detectability. This is to be contrasted with the high detectability of the fully forced signal in 1000-500 hPa thickness increase (red curve), whose magnitude is estimated to be 3.5 standard deviations of internal decadal atmospheric variability. Much of this fully forced warming signal in the

[2] A +20m change in 1000-500 hPa thickness corresponds to a +1K change in layer-averaged temperature.

polar cap arises from natural variability in global SSTs (NatSST) occurring principally outside of the polar cap. A mean thickness increase of 8.8m occurs in experiments subjected to estimated natural SST variability alone (green curve, see also section 2). Atmospheric transport processes across the lateral boundaries of the polar cap are the mechanism by which the polar cap primarily warms in these experiments, and contrasts with the mostly in situ warming resulting from Arctic sea ice loss. It is evident from comparison of the the two PDFs than the remotely forced signal is more than double the in situ sea ice signal of column Arctic warming. An additional signal of Arctic warming, having about 1.8m magnitude, can be inferred from the difference between the red PDF and the sum of the blue and green PDFs. This weak Arctic warming represents the overall effect of global SST increase and the direct atmospheric effect of greenhouse gas and aerosol changes between the two decades.

While the *local effects* of sea ice change on polar cap averaged tropospheric warming is found to be small, the question is open as to whether large amplitude regional circulation anomalies may have principally arisen due to *remote effects* of Arctic sea ice change. The spatial distributions of 1000-500 hPa thickness change observed and simulated are displayed in Figure 4. The forced signal (top right panel) exhibits substantial spatial variability in its magnitude that captures main features of the spatial structure of the observed change (top left panel). The large scale pattern including thickness decreases over central and western North America and increases over the rest of the Northern Hemisphere mid and high latitudes are at least qualitatively consistent with the contribution from natural SST change (bottom right panel). The signal due to sea ice forcing is also spatially inhomogeneous, though explains few of the key aspects of the observed regional change pattern. In particular, the sea ice effect is small compared to the effects of natural SST changes. An exception is in areas of maximum sea ice loss (compare figure 1, top and figure 4, bottom left) where local maxima in sea ice induced thickness change occur.

Overall, sea ice loss cannot explain the large magnitude of the observed regional high latitude thickness changes during OND, for example over the Eastern U.S./North Atlantic region, though there are alternate explanations for a forced change component. To illustrate further, Figure 5 presents the PDFs of simulated thickness changes for 270°-360°E and 45°-80°N together with observational estimates. Reanalysis values of 22m to 28m increases correspond to about 5 standard deviation departures as estimated from the control simulation (Figure 5 top, black curve). The observed change is thus unlikely due to internal atmospheric noise alone. The PDF of the fully forced experiment reveals a strong signal of tropospheric warming over this region whose mean forced signal of 13.2m, corresponding to about 2.5 standard deviation departures. In contrast, the regional thickness change due to sea ice loss alone is only about 2.1m, residing well within the spread of internal atmospheric variability. The results indicate that the observed regional North American/North Atlantic feature of circulation change (e.g. Francis and Vavrus, 2012, Barnes, 2013) characterized by a decrease of westerly zonal wind cannot be reconciled with the remote effect of Arctic sea ice loss. Furthermore, the sea ice signal would not be detectable relative to either the larger amplitude of internal noise or especially relative to the larger magnitude of natural decadal SST forced changes.

4. Discussion

An attribution study has been carried out to determine the magnitudes of various contributing factors to the recent tropospheric warming over the Northern Hemisphere polar cap region between the two periods 1979-1988 and 2003-2012. We have focused on 1000-500hPa thickness averaged over 60^o-90^oN and the OND season. This measure is an indicator of the column integrated atmospheric warming up to 500hPa over the Arctic region.

It is virtually certain that observed Arctic tropospheric warming could not have resulted from random atmospheric variability alone, but must have been strongly and primarily forced. The atmospheric forcing arises from changes in ocean and sea ice boundary conditions as well as through external radiative forcing due to changes in anthropogenic greenhouse gases and aerosols. The observed 1000-500hPa thickness increase of about 18m (~1K column averaged warming) between the earlier and later decades considerably exceeds the changes that would be expected from internal atmospheric variability alone (4m standard deviation of decadal averages). Our study further reveals that about 50% of the observed thickness increase between the two decades resulted from natural decadal SST variability over this period. This period was characterized by a shift towards the positive phase of the Atlantic Multidecadal Oscillation (AMO) and a shift toward the negative phase of the PDO. These phases project onto anomalously positive SSTs in the extratropical ocean regions that would favor enhanced poleward transports of warm air into the polar cap though tropical SST forcing may have also been important.

Our results further reveal that about 20% of observed thickness increase has likely resulted from sea ice loss alone. This finding agrees with the results of a case study by Screen et. al. (2013b) in which the authors determined that a sea ice contribution to tropospheric height increase over the Arctic in 2007, a year of extreme sea ice loss, was most likely not detectable due to large internal atmospheric variability.

While the *local effects* of sea ice change on polar cap averaged tropospheric warming are found to be relatively small in our analysis, the question has been raised whether large amplitude regional circulation anomalies over eastern North America and the North Atlantic may have principally arisen due to *remote effects* of Arctic sea ice change (e.g. Overland and Wang 2010; Francis and Vavrus 2012; Barnes 2013).

For the eastern North American /North Atlantic region, the observed OND increase in 1000-500hPa has been about 25m, which is a manifestation of an anomalously strong upper level anticyclone in that region during the last decade. Our model simulations suggest that about 50% of the magnitude of these regional thickness increases was likely due to forcing. However, sea ice effects accounted for less than 10% of the magnitude of this observed regional anomaly. The thickness (temperature) increase of 2m (0.1°C) attributable to sea ice effects is less than one-half the standard deviation of that region's decadal variability arising simply from random internal atmospheric variations. Remote sea ice loss in the Arctic is thus unlikely to have played a significant, and perhaps even detectable, role in the observed North American/North Atlantic atmospheric circulation changes between the two periods.

There is general consistency in results obtained from the two different models used in this study as well as findings from other modeling studies. Nevertheless, there are several sources of uncertainty that should be noted. Among those factors are uncertainties in the prescribed radiative forcings, and especially uncertainty in estimating the global warming component of observed SST changes. Various methods were used previously to determine the portion of the SST change attributable to natural SST variations. All prior studies first estimated a global warming change component and then calculated the natural variability as the residual difference from the observed changes. For example, Perlwitz et al. (2009) used the ensemble mean change of 20th century CMIP3 simulations to estimate the global warming component. Other studies (e.g., Pall et al. 2012) utilized several individual estimates based on different CMIP3 simulations to address uncertainties in the spatial structure of anthropogenically-forced SST changes. Here, we estimated the global warming component of recent SST change based on long-term observational trends, rather than using CMIP estimates because the new generation of climate model simulations (CMIP5) tend to overestimate SST trends over the recent 20-year period (Fyfe et al. 2013).

Other limiting factors are inherent in issues that arise when relying on climate models to draw inferences of cause and effect. To date, model studies have tended to find only weak impacts of sea ice loss on deep tropospheric temperatures, and in this sense our results are consistent with such a body of evidence. However, prior model studies have generally been limited in that they have been based on small samples for individual models, have drawn inferences based on averaging model results across members, and have mostly failed to examine the statistical distribution of individual ensemble members. Here we have examined the results from two different models, and affirmed a strong reproducibility of results. We have also used large ensemble methods, permitting quantitative diagnosis of large statistical samples from which we were able to examine the nature of Arctic warming in individual ensemble members. This presents a significant step forward in model-based approaches to understanding how the Arctic has warmed. The methods used herein thus offer a new perspective on the inherent atmospheric noise contribution to recent Arctic climate change, which we estimate accounted for about 25% of the observed tropospheric warming averaged over the polar cap. The limitation is that our estimates of such effects are purely model based, and it is currently difficult to verify from observations alone the effects of internal atmospheric variability. We would note, however, that the recent AR5 report of the Intergovernmental Panel on Climate Change (IPCC, 2013) states "Arctic temperature anomalies in the 1930s were apparently as large as those in the 1990s and 2000s. There is still considerable discussion of the ultimate causes of the warm temperature anomalies that occurred in the Arctic in the 1920s and 1930s." There is thus prior observational evidence that an important contribution to Arctic warming can originate from natural processes distinct from large-scale depletion of Arctic sea ice.

Another limitation of the current study is that we are unable to identify specific causes for the observed Arctic sea ice decline, since observed sea ice conditions were specified in the model simulations. Thus, the ultimate reasons for Arctic amplification in near-surface temperatures remain uncertain. The observed large decline in Arctic sea ice during the last decade is a low probability state in statistical distributions of coupled ocean-atmosphere models reported in CMIP5, which typically show slower rates of sea ice decline (Stroeve et al, 2012). One possible explanation for this discrepancy is that systematic biases in global model sensitivities to external radiative forcing have led to underestimates of the true rate of externally forced sea ice decline. However, our results suggest that a major fraction of Arctic tropospheric warming during the last decade was forced by natural SST variations outside the Arctic. A substantial fraction of the sea ice depletion during this period may thus have originated from natural decadal variability, rather than external radiative forcing alone. Such natural variations would not be expected to be captured in the CMIP5 simulations over this period, even in the absence of model biases. The question of the ultimate causes of Arctic sea ice decline therefore remains open. More research, using coupled climate models involving fully interactive sea ice, will be required to understand how natural variations in Earth's climate can drive extended periods of Arctic warming (and cooling).

5. Conclusions

A supposition that sea ice decline has been the primary cause for Arctic tropospheric warming is unsupported by evidence presented in this study--- sea ice loss is found to have explained about 20% of observed tropospheric warming over the polar cap. While observed near-surface warming over the Arctic is shown to have resulted primarily from in situ sea ice loss, the deep tropospheric warming is shown to have resulted primarily from remote processes operating mostly outside the polar cap. In particular, our results indicate that natural decadal SST variations drove atmospheric teleconnections which warmed the polar cap region, most likely through horizontal heat transports consistent with potential mechanisms for Arctic warming identified by Bitz and Fu (2008) and Screen et al. (2012).

Our results thus provide an alternate interpretation of Arctic-midlatitude interactions during recent years of warming. It has been surmised that sea ice losses during this period have been a primary driver of Arctic tropospheric warming which, through a cascade of processes, has led to more persistent and extreme weather conditions in mid-latitudes (Francis and Vavrus, 2012). In contrast, our findings suggest that over this period the Arctic troposphere has been mainly responding to rather than forcing mid-latitude weather and climate.

Our results have potentially important implications for the nature of Arctic tropospheric temperature change in the near future. Considering the relatively large contribution of specific natural decadal variability on the observed change in Arctic tropospheric temperatures since 1979, a slowdown of the Arctic warming or even a short-term cooling would not be surprising due to a potential reversal of the signs of the decadal modes.

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Table 1: Overview of model experiments

Experiment	SST	SIC	Radiative forcing	Number of runs/length of integration	
				CAM4	ECHAM5
CTL	1981-2010 Climatology	1981-2010 Climatology	1981-2010 Climatology	300 yrs	300yrs
FF	1979-2012	1979-2012	1979-2012	20 runs	20 runs
FixedSIC	1979-2012	1979-1989 Climatology	1979-2012	20 runs	10 runs
NatSST	1979-2012 with estimated global warming trend contribution removed	1979-1989 climatology	1880	20 runs	10 runs

Figure captions:

Figure 1: Change (2003-2012 minus 1979-1988) of October to December (OND) average. *Top:* Sea ice concentration (SIC) . *Middle :* Map (left) and zonal mean (right) total change of sea surface temperature (SST). *Bottom left*: Map of natural component of SST change. *Bottom right:* global warming contribution to zonal mean SST change. See text for detail.

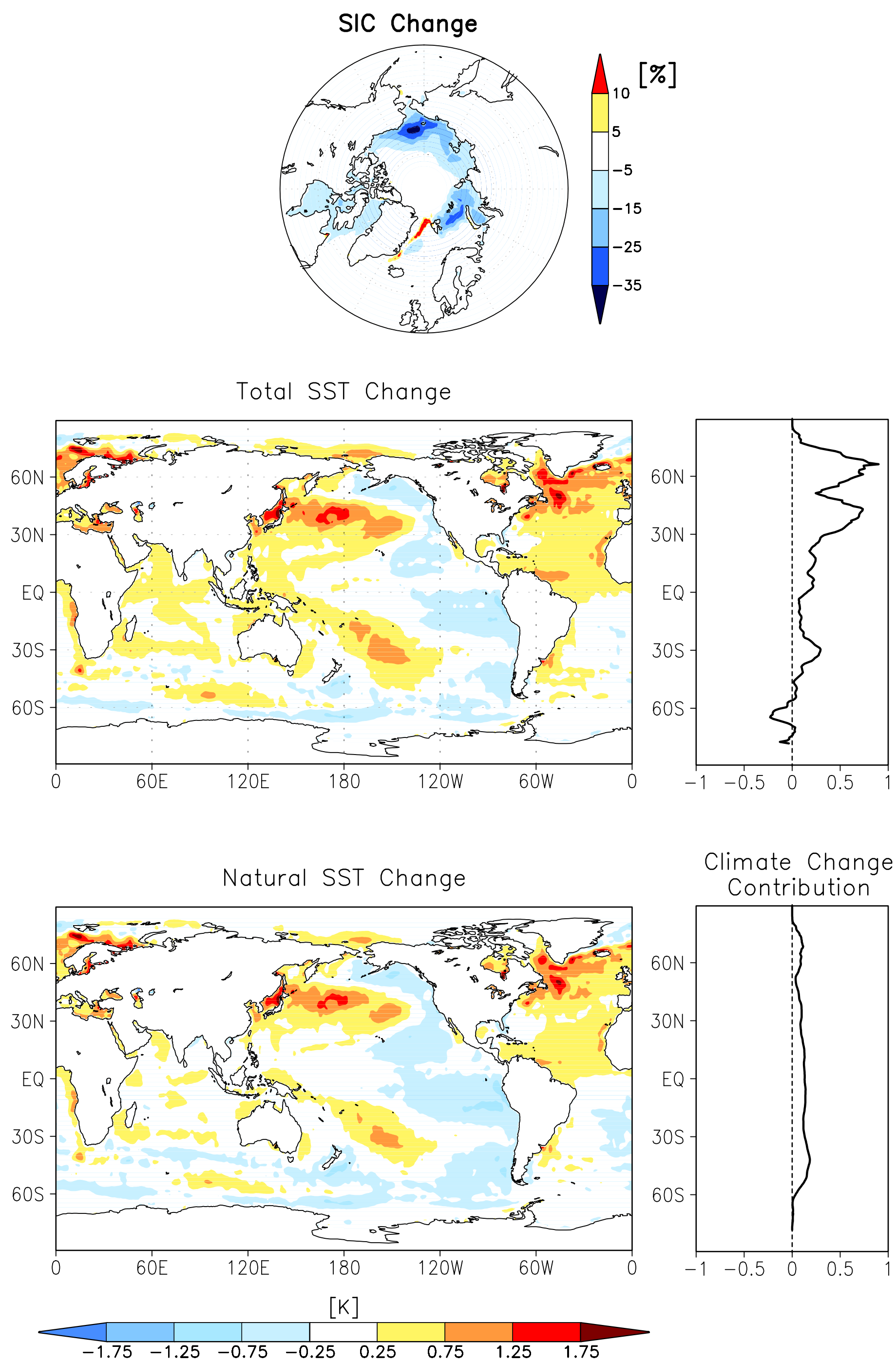
Figure 2: Latitude-height cross sections of zonal mean temperature change [K] (2003-2012 minus 1979-1988). *Top row:* Average of four reanalysis products. *Second row:* Simulated zonal mean temperature change based on observed SST and radiative forcing for CAM4 (left) and ECHAM5 (right). *Third row:* Same as second row but for fixed sea ice conditions. *Bottom row:* Simulated 2003-2012 mean contribution of sea ice change to atmospheric temperature change for CAM4 (left) and ECHAM5 (right). Non-linear scaling of the x-axes takes into account the area of the globe represented by the zonal mean.

Figure 3: Probability distribution function (PDF) of simulated change (2003-2012 minus 1979-1988) of October to December (OND) mean polar cap (60^o-90^oN) 1000-500hPa thickness [m].

Top: Estimated atmospheric internal variability (CTL, black) determined based on differences between decadal means of a 300 year control experiment and fully forced response (FF, red). *Bottom:* Estimates of sea ice effect (SI, blue), natural decadal SST change (NatSST, green). The PDFs are based on combining ECHAM5 and CAM4 ensemble simulations. Shown are also values of four different reanalysis products (red dashed marks).

Figure 4: Map of change (2003-2012 minus 1979-1988) of October to December (OND) mean 1000-500hPa thickness [m] over high latitudes. Shown are average of four reanalysis products (top left), simulated estimates (average of ECHAM5 and CAM4 ensemble means) of total forcing effect (Fully Forced, top right), sea ice effect (SI, bottom left) and natural decadal SST change (NatSST).

Figure 5: Same as Figure 3 but for the area 90^{o}W-0^{o}, and 45^{o}N-80^{o}N.



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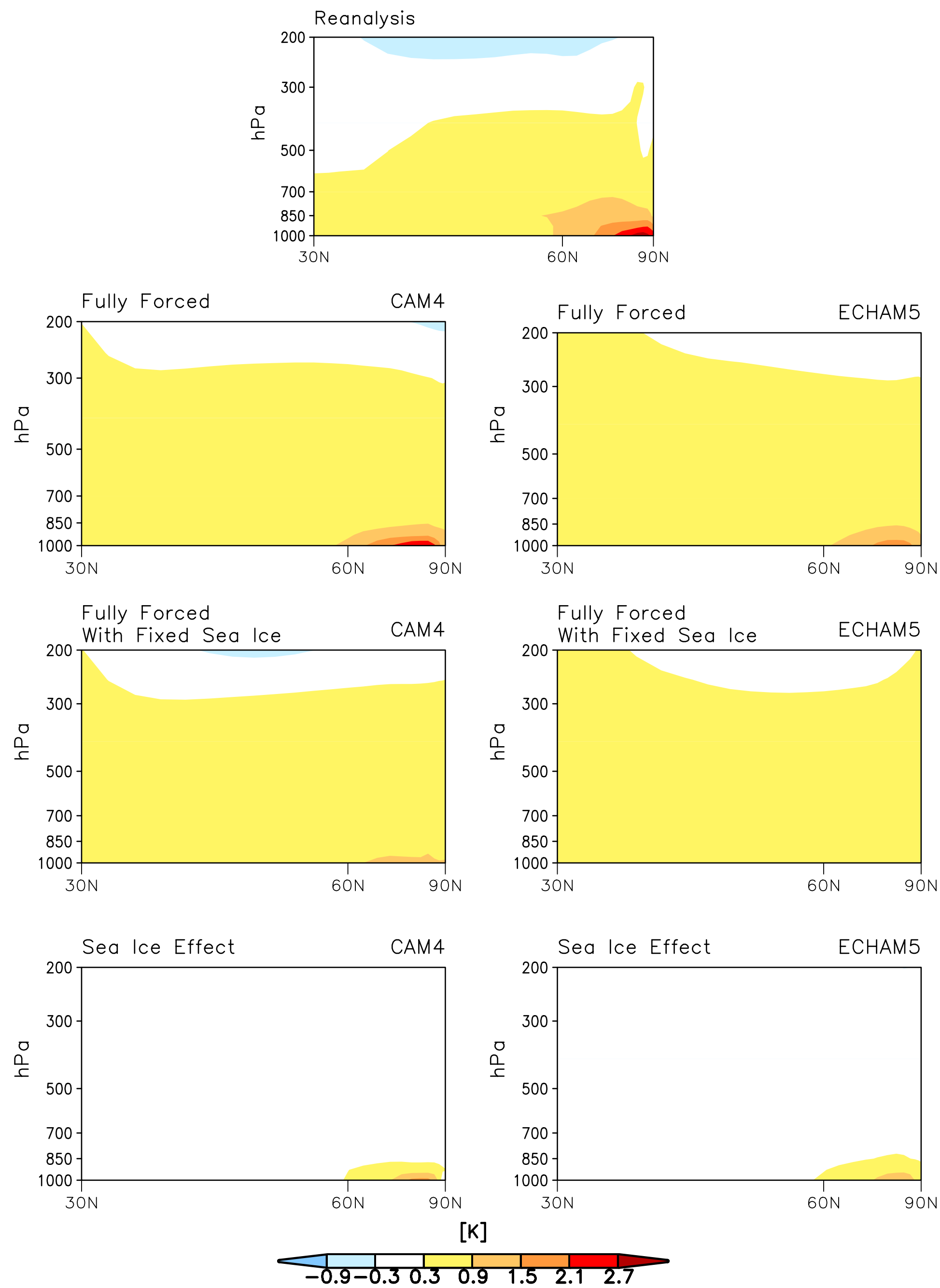

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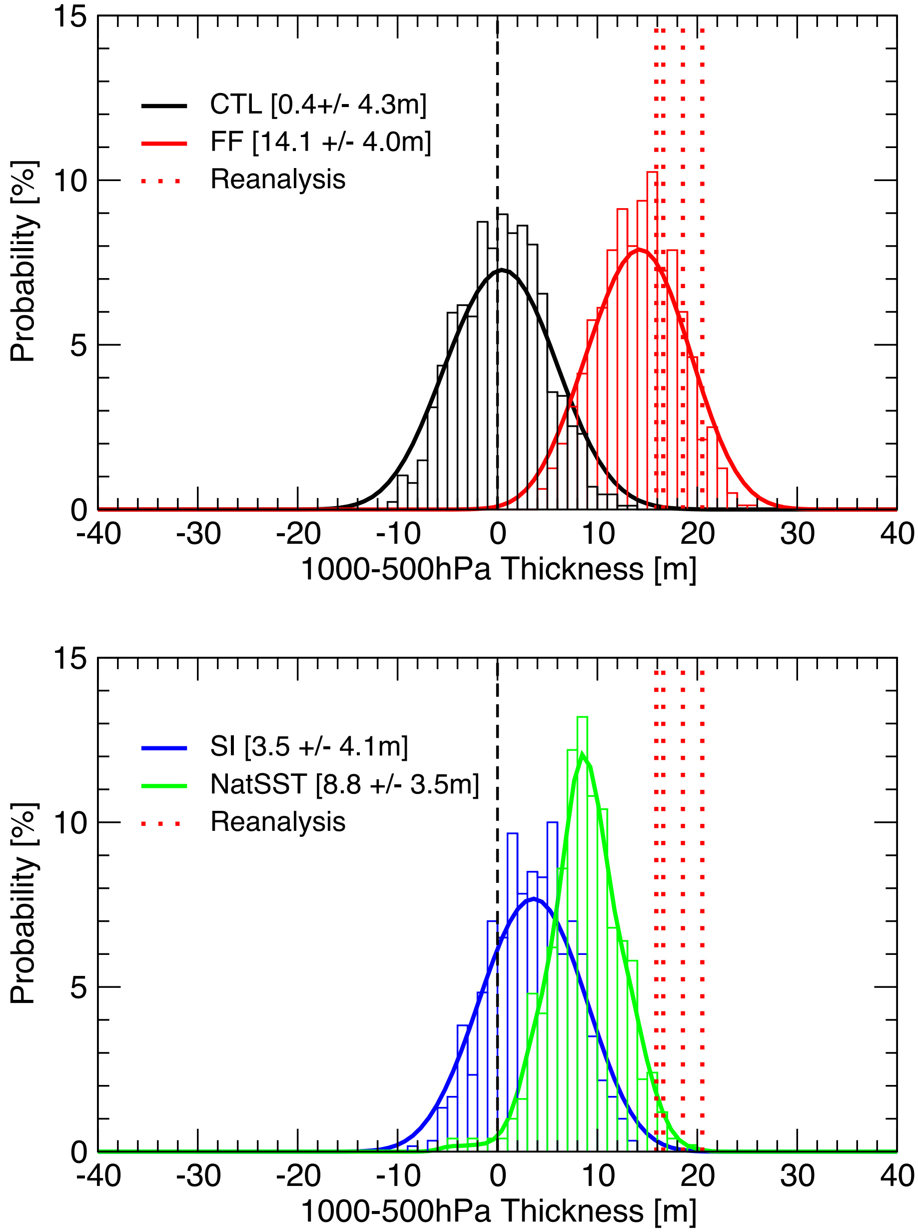

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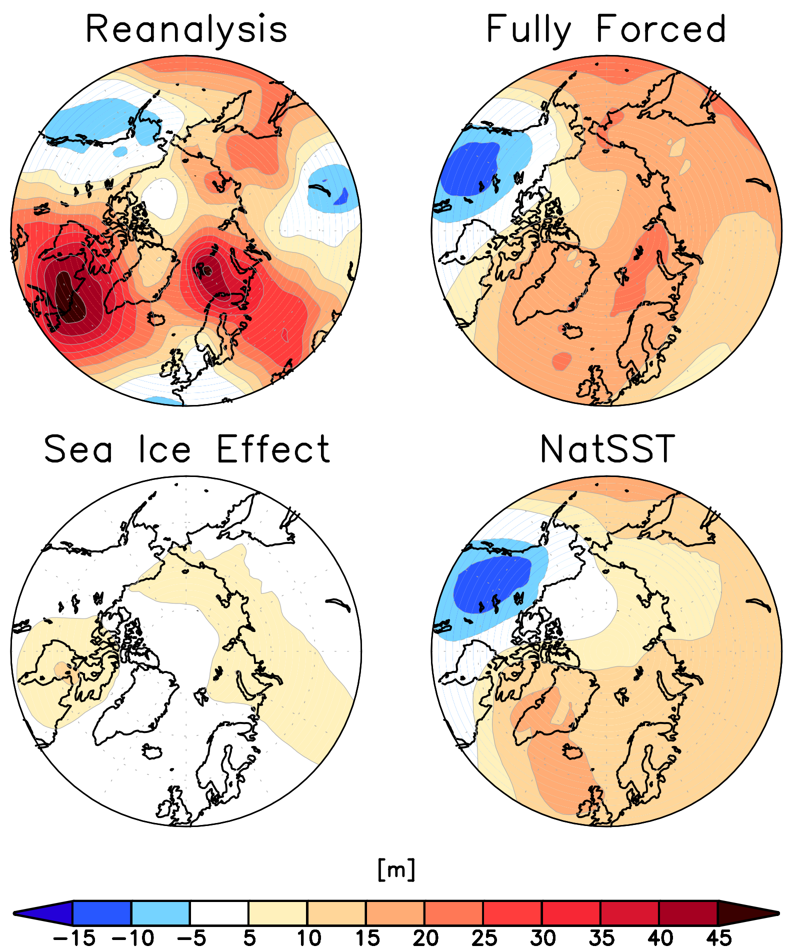

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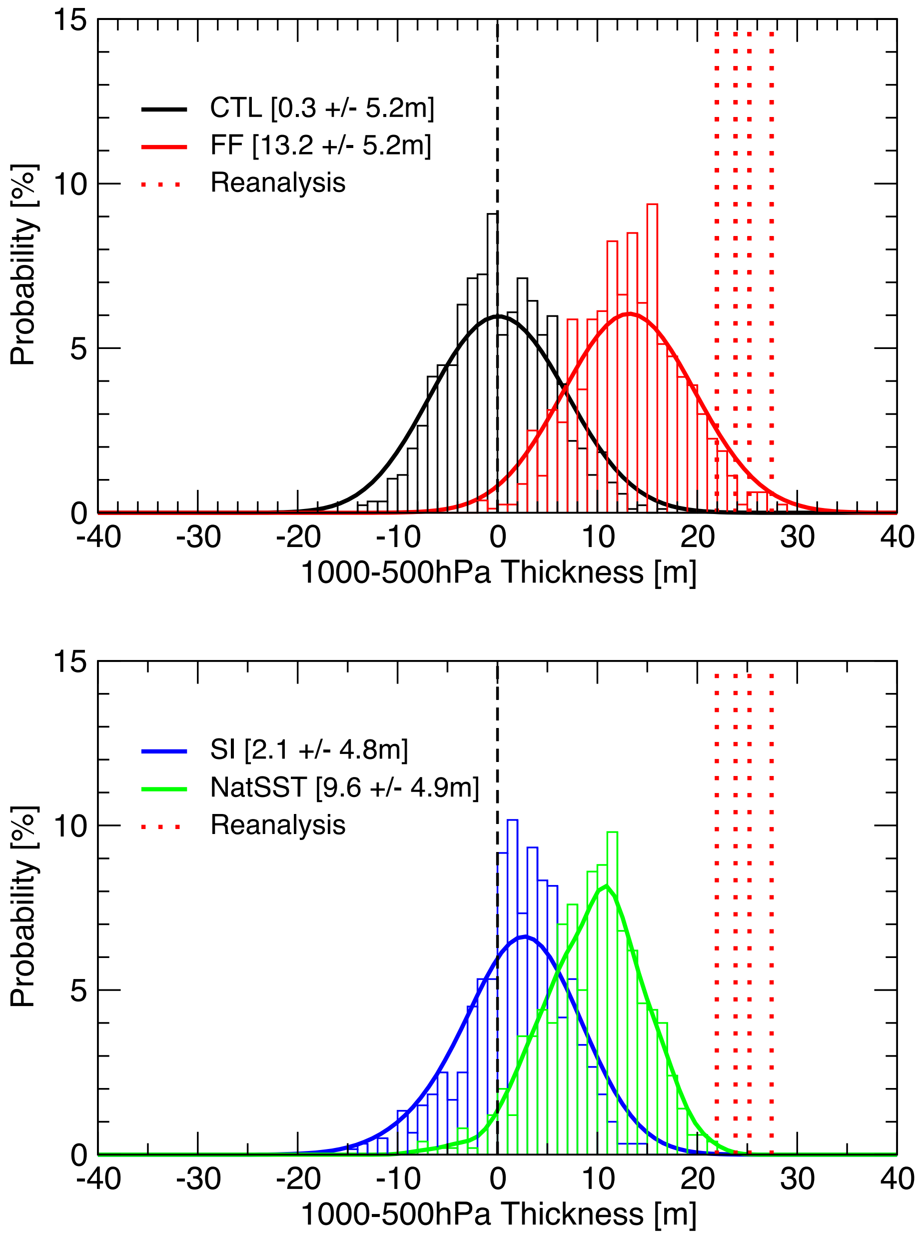

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